Mass-interaction model of emergent collective phenomena

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Abstract

This paper is a position paper on the concepts of emergence and individual / collective paradox, from both philosophical and experimental point of view. It presents successively: (1) some sociological and philosophical issues related to collective emergent behaviors; (2) a non-conventional point of view of physical mass-interaction modeling as a cellular automata system; (3) a proposition of a generic physical mass-interaction model for emergent collective phenomena able to render the main expected figures of non-deliberative emergent collective phenomena as those that define crowd behaviors.

Keywords: physical mass-interaction modeling, emergent behavior, collective phenomena, crowd dynamics.

1 Introduction

Usually, emergent collective behaviors are associated to behaviors of living beings and it is commonly considered that the best types of models and concepts adapted to render them are behavioral models, as those based on agents concepts, developed by artificial intelligence, or artificial life. Conversely, physical models or physically-based models are usually restricted to the modeling and simulation of non-living nature, or animation of non-living behaviors.

In this paper, we will try to demonstrate that this association between a type of dynamic phenomenon and a type of model is an a-priori categorization based on two main misunderstandings: misunderstanding of what is "a crowd", and misunderstanding of what is "a physical model". To achieve this theoretical and pragmatic aim, we will presents successively:

(1) Some sociological and philosophical issues related to collective emergent behaviors by comparing the main sociological and philosophical points of view about what do collective phenomena and emergent property mean. We will present then the global incidence of such a point of view on the modeling concepts. We will analyze the different types of collective features, distinguishing between collection of non-deliberative action and common action with deliberative activity or explicit symbolic common goal.

(2) A non-conventional point of view of physical particle modeling as dynamic cellular automata systems derived from philosophical issues on physical modeling. We called them Newtonian Networks and we will compare them with other types of cellular networked automata, neural networks and agent based networks.

(3) A proposition of a generic physical mass-interaction model for emergent collective phenomena and its application to human crowds' behaviors. We will start with the specification of the dynamic emergent features characterizing a crowd in the sense of a class of phenomena exhibited by a set of individuals. We will design a minimal and generic particle physical model and we analyze the results obtained from simulations of this model.

(4) We will show that this model is able to render the main figures of non-deliberative emergent collective phenomena as those that define crowd behaviors.

2 Sociological and philosophical issues

The three terms, « collective », « emergent », and « phenomenon », as well as their association, rise some epistemological and linguistic problems. We will examine here some relevant and differentiating aspects able to clarify the properties of the modeling system and the types of patterns we have to render by means of the simulation of the selected types of models.

2.1 About "collective" and "emergence"

Two theories are generally opposed concerning the conditions from which the "collective phenomena" are emerging. The first one is Durkheim's theory [1] by which the collective is defining the individuals. The individuals encode specific collective behaviors through collective representations and cultural rules. The capabilities to exhibit or the follow collective behaviors seem "programmed" as specific functionalities inside the individuals. Conversely, the post-modernism, based on the prerequisites of the individual, assumes that the collective is built from the individual properties. In both cases, the relation between the individual and the collective remains unresolved. This unsolved paradigm is illustrated by the usual paradox: from what number of grains we obtain a pile of rice, by adding grains? And conversely, to lead to the Durkheim's point of view, from what number of grains, a set of grains is no longer a pile of rice, by removing grains. That is the notion of *emergence*, well supported by the literary figure of "sorite". Let elements (units, atoms, etc.) that have the property "non-P". When a set of such elements exhibits the property P, the property P is - strictly speaking – "emerging". In other words [2], emergence is a process in which a collection of interacting units acquires qualitatively new properties that cannot be reduced to a simple superposition of individual contributions. This figure of "sorite" can be expressed from two points of view: the point of view of the individuals and of the collective.

2.1.1 Emergence expressed from the point of view of the individuals (A)

It is based on "action" or "intentionality" of the individuals. Here, we have to distinguish between (A1) the action from several and (A2) the common action with others.

- A1: Action from several

There is no collective aims or rules, explicit or implicit. Each element follows its own aim. A subsequent issue is that the conditions of this type of collective action are external to the individuals and are not modified by the individuals during their actions. Typical cases are the highway motor driving, the dynamics of financial markets, and the free walk of a set of persons on public spaces. Except specific individuals, as leaders who personify the goals, the individuals do not play predetermined and dedicated role in the collective action. According to Pierre Livet [3], "the collectives remain virtual", in the sense of "the individuals have any proof or any appreciation, knowledge of the real existence of the collective".

- A2: Common action with others

Conversely, the common action is based on two prerequisites: the definition of a common goal and the acceptation by the individuals to collaborate actively with the others to reach this common goal. Two different sub-cases can be distinguished: (a) when the individuals are (or are not) identified and play explicit role and when they can be unidentified and interchangeable (for example, in space or in time). Typical examples of (a) cases are collective sports (football, basket ball) or social cooperative works. Typical examples of (b) cases are crowd in social public demonstration as strikes. In both, the goal is clearly identified and known by all.
The first case, "action from several", refers undoubtedly to the point of view of modernism: the collective organized figures and patterns that appear are not defined inside the individuals. The individuals are "free" of the collective. Strictly speaking, as defined before, these collective figures are emerging from the set. The second case is ambiguous. Only the first sub-case (a) refers clearly to the Durkheim's point of view: each individual has a precise role in the population.

2.1.2 *Emergence expressed from the point of view of the collective (B)*

It is based on the evolution or the dynamics of the set. It can be analyzed in terms of what we call (B1) symbolic communities and (B2) reactive communities.
In symbolic communities (B1), the symbolic or deliberative activity (discussions, negotiations, orders, etc.), is a necessarily (but not sufficient) component of the interaction between individuals.
Conversely, in reactive community (B2), the symbolic or deliberative activity is not a necessarily component of the interaction between individuals. In such a case, even if it is not sufficient, the necessary component of the interaction is based on the low-level action/reaction principle. In living beings, the instinctive physical sensory-motor interaction between elements (individuals) and the others (other individuals or environment) is of this type.

2.2 About "collective" and "phenomena"

Let us take the example of the human crowds. Two theories are confronted. The common point of view calls "crowd" a sufficient number of human beings confined in a same environment with a density greater than a certain threshold. This definition can be called "a material definition": a crowd is a "thing" or a set of "things". From the point of view of the sociologist Gabriel Tarde (1843, 1904) [4], with his famous distinction between the "public" and "crowd', or of the sociologist Pierre Livet [3] with his concept of 'communities as virtual", a crowd is not a "thing" or "a set of things", but a phenomenon. This means that if a collective is defined by the emergence of a new property, thus it is not sufficient to agglomerate sets of elements to obtain collective features.
As example, a single hair has not the property to be a hair. The collective phenomenon – the relevant and organized collective pattern is " a set of single hair" organized as a hair. It is obvious that all the sets of single hair cannot be a "hair". They can be a "tuft of hair" or other arrangements. Only specific sets can be identified as "a hair". Similarly, it is not sufficient to have a lot of grains to have a pile of rice. A pile is a specific class of spatio-temporal patterns with precise structure and specific evolution: symmetric pile, auto-similar growing, surface chaotic avalanches, etc. Hence, it is not sufficient to have a lot of elements to obtain a new property leading to collective organization. And far away, when they are, a set of elements could exhibit several classes of generic collective behaviors.
That is the basic idea of the assumption "a crowd is not a thing but a phenomenon": a crowd is a specific behavior exhibited by several individuals under some specific conditions. In addition, several classes of collective behaviors can coexist simultaneously. The most relevant of them is the distinction made by G. Tarde between the "public" and the "crowd". Behind these two words, Tarde pointed the distinction between two classes of collective phenomena consistently different: those called "public", as listeners in a concert room and those called "crowd" as when they are leaving the concert room or when they applauds with the Ola or the recall effects. In the "public" collective attitude, there is a superposition of a crowd effect (the common silent, the common attention, etc.) and of an individuated shared behavior (each listening differently of each other). When they are applauding, the "Ola" triggering and propagation effect, or the recall applauding effect with its characteristic periodicity, address the "crowd effect". These effects are similar of those observed in the public places, as stadium with global motions. They are mainly characterized by a radical loss of individuality in the behaviors. Differently, in the "public" behavior, each individual can remain more or less distinguishable, resisting to the global behaviors and exhibiting some lack in cooperative attitudes.

2.3 Methodological issues on modeling

According to these opposite points of view, three main types of methodology of modeling can be distinguished:
• One based on the modeling of a specific phenomenon, called by Lantin [5] and Fleischer [6], "one shot model": the model leads to model as the best one phenomenon (for example: model of specific turbulences in fluids)
• One based on the modeling of the "things" that produce phenomena. Differently than the previous one, this type of model exhibits a new property that is the "generativity". That is usually the meanings of the term "simulation"

on which the simulacrum is expected to have the same level of generativity that the real simulated thing.

• One based on the modeling of the class of phenomena, in the sense of a class of phenomenological invariants. Instead of the "one shot type model", and similarly with the "real cause modeling", it exhibits the maximum power of generativity. This type of model is situated at an upper level of abstraction of the two firsts. It supposes to have at disposal a typology of relevant features characterizing classes of observed phenomena. Thus the modeling process aims to model all these specified features, whatever the real things that produce these features.

We can observed that:

• the first "object or thing based" definition of the crowd is related to the first attitude of modeling, from which all (i.e. the maximum) of objects' behaviors are expected : individuals, deliberative, reactive, etc…

• the second "phenomena based" definition of crowd is related to the second attitude of modeling, from which all (i.e. at least the necessary) the relevant features defining a class of phenomena are expected. It needs to pre-specify these relevant features as properties of a class to be modeled by a generative model. For example, in the case of crowd behavior, these features should be: laminar flowing, soft and long-distance avoidance with speed and orientation anticipation, sudden and short-distance avoidance, merging, jamming with collapses, flow auto-rerouting, etc.

Let us continue with the example of the panic situation, frequently addressed as one of the main crowd behaviors. Nevertheless, we can notice the state of "panic" addresses more to individual level than the global macroscopic collective level. Indeed, at the collective level, the panic state of individuals could produce several different observed patterns: (1) fluxes running in a same direction, (2) disordered motions like Brownian molecules motions, (3) competitive fluxes forcing in the same direction against others, etc. Conversely these collective figures may appear in absence of panic. We may see these figures as panic effects only when they lead to dangerous situations for the individuals or groups of individuals: (1) when the fluxes are throwing on an obstacle (walls, closed or small doors) (2) unable to find the safe solution, (3) associated with struggle of life. This analysis proves that the term « panic » refers more to the individuals than to the collective.

We can now try to associate sociological concept with types of models and types of effects. For example, geometrical and physical models in Computer Graphics are mainly oriented to the "object modeling". That is also the same in the main conventional use of "agent based model", in which the model has to take into account the intrinsic agent's properties. Conversely, the use of genetic or physical algorithms as process applied to simulate "non-genetic or non-physical things", (optimization problems solving, parameters' convergence, simulated annealing, etc.) refers more to the abstract approach based on modeling a class of phenomena. Other generic and « effect based » models are models as L-systems or « Cell Programming Language» [6]. Physical mass-interaction models are of this category.

3 Physical modeling

3.1 Philosophical and linguistic issues

3.1.1 Physical modeling: two meanings

Usually physical modeling is understood as a system to represent the natural phenomena. That is obviously the case in the experimental science called Physics. Nevertheless, there is a confusion between what it is modeled – the nature, precisely called in ancient Greek "Physis", in the sense of "being done" – and how it is modeled – that refers to a part of "Mathematé" (in ancient Greek) - as the process to study and represent. Thus, there are two meanings of "Physical model":

• a formal representation system with which the nature can be modeled : we have then to understand "model of physis"

• a formal representation system based on specific properties referred as "Physics" : we have then to understand "physical" as a quality of the modeling system and of the model.

In the first meaning, all the models that are able to represent natural phenomena can be called physical models. For example, in the modeling of physical optical phenomena, we can use geometrical optics (geometrical description) or physical optics (Maxwell equations). The qualifiers "geometrical" and

"physical" point the type of model and not the type of phenomena.
In the second meaning, as arithmetic, geometrical, logic or genetic model, there is any contra-indication to use physical model various type of phenomena (static as well as dynamic).

3.1.2 Properties of Physical modeling as a general formal representation system

What are the specific properties of a "physical model" as a general formal representation system? Let us restrict this theoretical issue in the field of motions. In this field, "Physical" is synonymous of "dynamics", i.e. based on the concept of forces. In the Newtonian point of view, based on the action-reaction principle, the force can be seen as a formal descriptor of a correlation between two observed evolving phenomena. Thus, the strength of the Newtonian formalism is in the specification of two formal dual variables:
• Extensive variables (EV), for example positions or velocities. Evolutions in space of such variables are observable.
• Intensive variables (IV), as forces, called also "influences" before Newton, that are formal algebraic descriptors of what it is called "interaction", i.e. bilateral influence of two observed phenomena: the evolutions of EV1 and of EV2 are symmetrically correlated. The action-reaction principle is the simplest axiom declaring that these two influences are equal.
Thus, physical modeling can be seen as an abstract representation formal system by which we describe algebraically the dynamic correlation between two (and further any number of) dynamic phenomena, whatever they are, this algebra being based on two dual variables: one (EV) describing the intrinsic evolution of the phenomenon from the influences (IV) of all the other phenomena, and one (IV) describing the mutual influence between each pair of them from the evolution of extensive variables (EV). All the rules that are involved to model a dynamical system are rules that links EV and IV. These rules can be called Physical rules. We can notice that natural phenomena are obviously represented (modeled) in Physics (Mechanics, Electricity, etc.) by these types of abstract rules.

3.2 Physical mass-interaction modeling as a type of automata cellular network

Referring to the property of Emergence as a primary property of collective phenomena, cellular networks, as networks of interacting "units", are the best candidates to model collective effects in an generative way.

3.2.1 Newtonian Networks as Dynamic automata

From the abstract point of view developed in the previous paragraph, we propose a representation of Newtonian propositions as on networked functional interconnected components. Similarly with the well-known Kirschoff's network in Electricity, a formal physical model for spatio-temporal phenomena will be a network called Newtonian network, composed of two dual components (figure 1): (1) behavioral components and (2) interaction components calculating specific physical rules of correlation (between distances, between velocities). The data that is circulating and exchanged each time between these components are the dual variables: extensive variables (EV) and intensive variables (IV).
• The behavioral component (i) calculates at each time the behaviors according to all their bilateral influences from each other: Fi <-> Xi.
• The interaction component calculates the correlation between the observed behaviors (i,j): Fi,j <-> R(Xi, Xj) and Fi,j + Fj,I=0.
That is why Newtonian formalism is an interaction based paradigm, and should be an excellent candidate to model all the dynamic phenomena with interactions between behaviors.
To represent dynamic phenomena produced by real systems, the necessary and sufficient elementary components are the three basic rules linking intensive variables and the three basic extensive variables: positions, derivative of the position (velocity) and derivative of the velocity (acceleration). Each of them is a finite state automaton, which calculates an elementary differential equation (figure 1).
We obtain a cellular automata network, called Newtonian Network, in which each cell calculates an elementary differential equation: d2/dt2, d1/dt1, d0/dt0.
The circular component represents the basic behavioral inertial component. It receives the influences, adds them and produces the extensive variable. The ellipsoidal component

represents the interaction component. It receives the two behavioral extensive variables that are correlated and it calculates the intensive variable representing the observed correlation (in distances and/or in velocities.

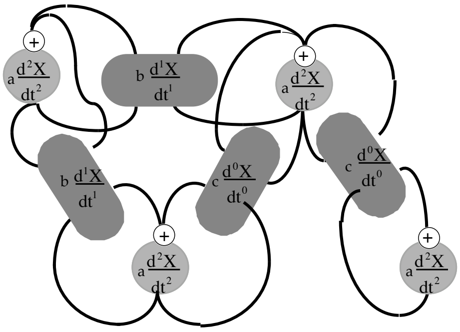

Figure 1: Newtonian dynamic automata networks

Conversely to the usual differential analytic expression, this networked representation allows to represent and calculate easily non-linear interactions. The modifications, in space or in time of the parameters (a, b, c) allow to represent any kind of non-linearity.

Comparison with other types of Cellular Automata Networks

The following table (Figure 2) sketches the two main types of Cellular Automata Networks: the well known neural networks and the agent-based systems seen as networked elementary units.

• Neural network (Figure 2, left) are composed of connected logic automata. The node is the computing elementary element. On each node, all the influences of other nodes are summed according to a weight α for each. To comparing with the Newtonian networks, we identify respectively the inertial lass component, and the interactions components of the Newtonian Networks with the nodes of the neural network and the connections of the neural networks. Newtonian nodes and interactions work. The data that circulate in the network are logic data as in Newtonian networks they are real. Node and connections automata are elementary logic automata. Inertial components and interactions components are differential equations. The elementary components are more complex in the Newtonian network that in neural network. The interaction components can be seen as consistent analogous weighting of influences. In both cases, the influences are summed on the elementary behavioral component.

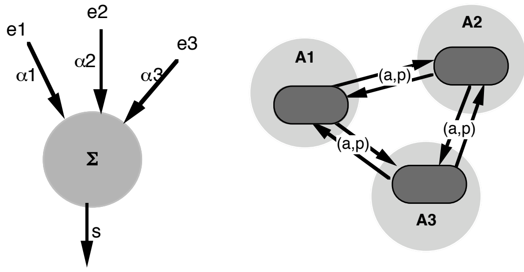

Figure 2: types of cellular automata networks. Left: logic automata (neural networks). Right: symbolic automata (Agent networks).

• In Agents systems (Figure 2, right), the nodes are the agents. They interact through action-perception metaphors. The agent computes the action from the perception. This means that, conversely to neural networks or Newtonian dynamic networks, the correlation between the agent's behaviors is defined "inside the node". The owner rules of the agent interpret the relation between its inputs and its outputs. By principle of a decisional system leading the individual, it cannot be an interaction symmetrical system that is necessarily independent of the individuals. On agent-based systems, physical behaviors are only considered at a low level only to create motions. In the Newtonian networks, if we identify the agent with the inertial element, action-perception metaphors will play through the action-reaction principle via the dual variables: extensive variables can be seen as observed (perceived) variables, and intensive variables can be seen as produced variables, that will influences the other "agents". The behavior is based on an elementary differential equation that computes the second order evolution of the behavior, and not an elementary decisional process.

To conclude, Newtonian networks (Figure 1) are similar to neural networks. The main differences are in the explicit typing of variables in the first and that the elementary computation are an order complex in the first than in the second. The Newtonian networks are also similar to agents' networks. Both have variables' typing. They differ by the process calculated by units: differential calculation for the first, other kind of calculation that does not need symmetrical interaction between agent.

4 Mass-interaction modeling of emergent crowd behaviors

4.1 State of the art

Numerous works have been published in the area of crowd simulation. They refer to different modeling processes, i.e. different ways for analyzing and understanding the relevant features of collective phenomena.
Currently, crowd behaviors referred to three main approaches:

- A kinematical approach, in which key frames and interpolations preset the animation.
- An approach based on agent systems in which agents are managed in real time by rules of behavior defined with automata.
- An approach with a particle-based system where the particles are animated in real time by the application of different forces.

In the kinematical approach, the evolutions of the displacements are explicitly defined by temporal evolution functions. It attempts to produce the effects without considering their causes: it is *a phenomenological approach*. Musse and al. [7] automates the determination of trajectories for a group of characters by providing a set of Bezier curves that do not collide. The strength of the kinematical approach is to be totally controlled. Conversely, it is not suitable to simulate unpredictable collective behaviors. The two other methods are *generative approaches*, describing possible causes that may produce the desired effects. The strength of generative approaches is that several complex behaviors can be synthesized with a single model. Its weakness is to find this model. Indeed, since crowd behaviors are essentially emergent, generative approaches such as agent systems or physical models are most appropriate to produce these kinds of phenomena.
Agent models are best adapted to model behaviors with strong individual differentiation, such as cooperative behaviors in which the actors' intentions play a significant role (collective sports, joint action, etc.). Thalmann et al ([7], [8]), Devillers et al [9], and Donikian [10] use complex finite automata to determine actors' behaviors. These automata represent intelligent autonomous behaviors defined by sets of clever rules. Interactions between persons are modeled by symbolic rules and constraints. Similarly, Lantin [5], Fleisher [6] modeled self-organizing structures for the simulation of the growth of living organisms.
Reynolds [11] addressed the first the modeling of emergent collective phenomena by agent-based systems. He extended this work by adding a metaphoric steering motor force to the agent-particles [12]. Goldenstein [13] used a similar agent-particle system with different collision detection and path finding techniques.
As developed before, in crowds, the basic phenomenon is mutual, implicit, non-conscious and non-deliberative adjustment, in which collisions and avoidance are implicitly included. This mechanism of auto-adjustment may be simulated with physically-based particle models incorporating two elementary repulsive and attractive forces, as it is largely used to simulate traffic jams [14] or sand dynamics [15].

4.2 Specification of dynamics effects

In the method proposed here, based on generic physical models to model features of class of phenomena, the main difficulty is the specifications of these features. In the field of collective behaviors, no sufficient specifications exist nowadays. The main observed phenomena developed for controlling motorway traffic or for the safety of public spaces (stadium, rail stations, etc.) are usually: short-distance avoidance, jamming, flowing with processions, chaotic dispersion. To compensate this lack of knowledge and categorization by providing by ourselves plausible observed categorizations, we added:

- Medium-term or long-term distance avoidance, with anticipation effect in trajectories and in velocities (long distance small trajectory rerouting, slowdowns / acceleration)
- Jamming, with internal sub-groups collapses and unpredictable border flowing
- Propagation effects as the “Ola” effects,
- Flow penetration and mixing,
- Global flows interaction, with flow laminar rerouting, curls and vortices.
- Velocity and spatial coordination: step adjustment, psychological compressibility, and psychological incompressibility threshold.

4.3 Crowd emergent effects simulation by means of Newtonian Networks

According to the sociological point of view presented before, a set of units leads to a crowd behavior by loss of individuality. As example, in a choral, the properties of individual as vibrato, have to be removed as more as possible, to avoid cacophony. In the queue, individuals' behaviors are risky for all the other individuals. More the individuality of unit is, more impossible will be the collective non-deliberative organization.

4.3.1 Unit (or characters) modeling

Thus, it should be sufficient to model the set of persons by a set of similar units. In our mass-interaction model, the elementary unit being punctual inertia, we model at the simplest level, characters as punctual inertia, which calculate positions, through acceleration provided by the sum of forces (influences).

4.3.2 Interaction between units

All these units are in bilateral automatic interaction, according to the action-reaction basic principle, to regulate the correlation between their behaviors. Two complementary interactions should be sufficient:

• Family of correlations in distance (Figure 3 left) usually called "elastic effects" or potential interaction. They will be able to regulate:

- The spatial correlation between individuals: attraction, repulsion, cohesion, etc.
- The immaterial psychological volume with dynamic properties as non-penetration, psychological observed elasticity (rigidity) and compressibility (incompressibility)
- Automatic avoidance with short-distance, medium-distance, long-distance anticipation

Potential interactions Viscous or dry friction interaction

• Family of correlations in velocities (Figure 3, right), commonly called "viscous or friction effects (or interaction)". Finite state automata can generally represent them. They will regulate correlations as:

- Effect of anticipation on the velocities during the avoidance process (slowdowns before the encountering, re-acceleration after)
- Adjusting velocities (walk at the same step, etc.)

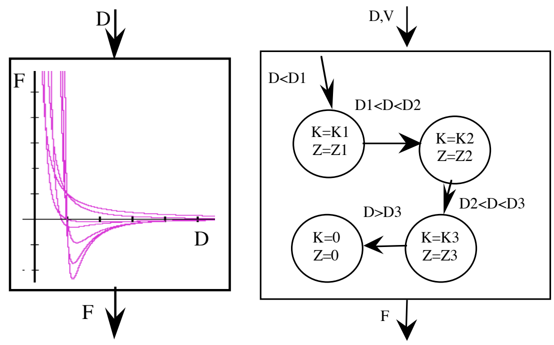

Figure 3: Interactions family between characters. Left: potential interaction. Right: viscous or dry function interaction.

4.3.3 Obstacles modeling

The obstacles are modeled as persons by set of punctual masses. The obstacles dynamic functionality is to restrict the configuration space and to work against motion. They can be fixed or mobile material objects, but also immaterial things as sunny and warm areas, winded area, and finally combination of material object and immaterial things. For example, a fountain can be modeled as an evolving zone including the fountain itself and surrounded by zone of dispersed water. The mist that is cold in winter will be an obstacle to be avoided. But in summer, it will become a fresh and pleasant zone that should not be avoided.

4.3.4 Characters/obstacle interaction modeling

The interaction between obstacles and characters are modeled with similar interaction functions. For example, wind will work against characters' motion as other characters flows.

4.3.5 Elementary intention to move

The only minimal autonomous rule to be implemented in the characters is the elementary intention to move. For the first experiments, it could be implement by means of attractive or repulsive external targets, initial velocities, injecting process that inject some characters in the confined expected environments with initial density and/or initial velocities.

4.4 Results

The snapshots of simulations presented at the end of the paper show the obtained collective phenomena. To facilitate their observation, we have to use several types of visualization: (visu1) points that reveal more the absolute and relative localization, (visu2) parts of trajectories that reveal more the dynamics of the avoidance, of figures of flowing, etc and (visu3) humanoids with which we will compare better with human crowd observations.

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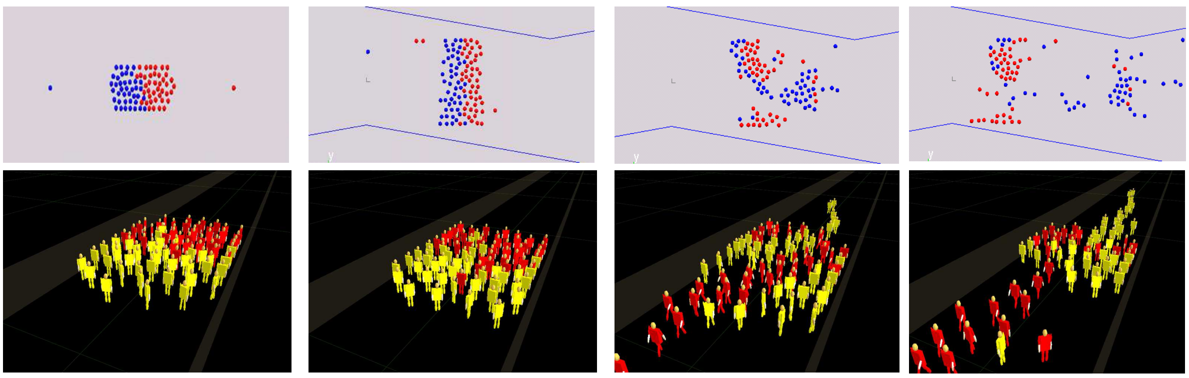

Figure 4: Simulations of meeting of two dense flows in a more (down – visu3) or less (up – visu1) straight road: - Constitution of a blocking jam
- More or less infiltration with internal curling rerouting of individuals

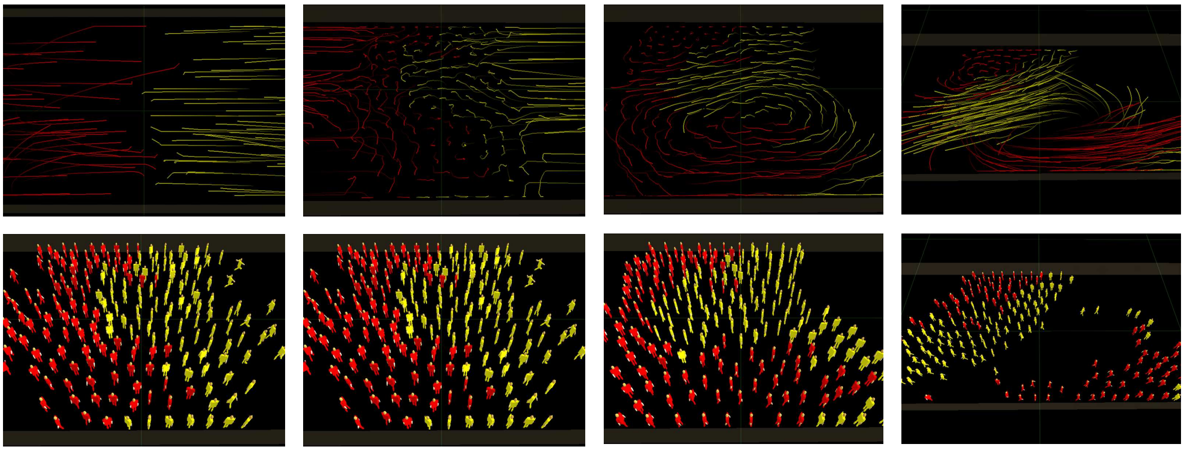

Figure 5: Simulations of meeting of two very high dense flows in a straight road - visu2 (up) visu3 (down). Increasing the density, increase the collective organization: less infiltration of the two groups, global rerouting of flows with important curls and vortex at the cross point.

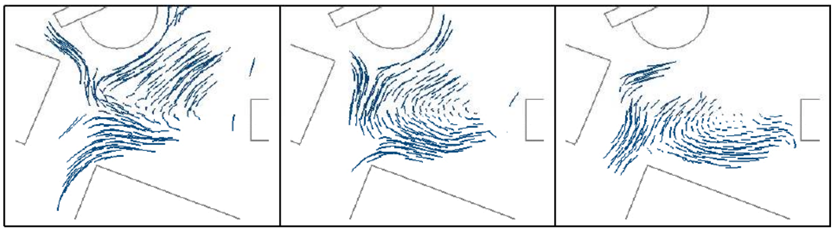

Figure 6: Simulations of meeting of three dense flows crossing in a square – visu2:
- Constitution of files and queues.
- Global laminar rerouting of the flows with vortex at the cross point.

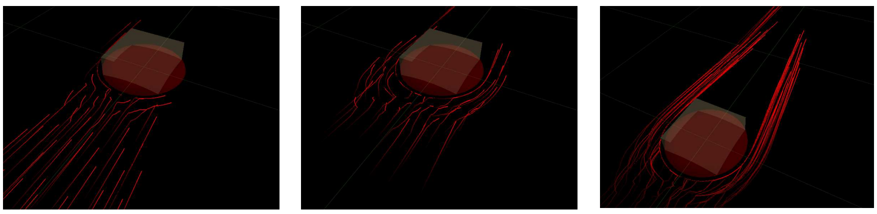

Figure 7: Simulations of flow thrown on a fixed small obstacle - visu2. Notice the laminar flowing during the avoidance.

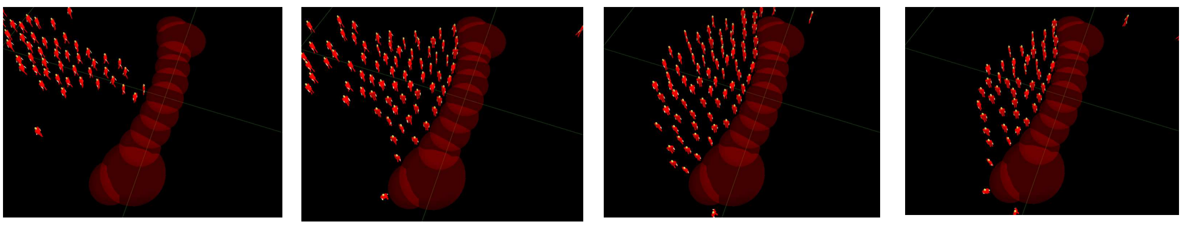

Figure 8: Simulations of flow attracted by a fixed large obstacle (visu3):
- Constitution of a well-formed pile (symmetrical as in granular materials)
- Constitution of sub-groups (cf. animation)
- Chaotic escapement on the boarders.